

Biomining - A Useful Approach Toward Metal Extraction

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Abstract: Biomining is the extraction of specific metals from their ores through biological means usually bacteria. Although it is a new technique used by the mining industry to extract minerals such as copper, uranium and gold from their ores but nowadays biomining occupies an increasingly important place among the available mining technologies. Today biomining is no longer a promising technology but an actual economical alternative for treating specific mineral ores. Traditional extractions involve many expensive steps such as roasting and smelting, which requires sufficient concentrations of elements in ores while low concentrations are not a problem for bacteria because they simply ignore the waste which surrounds the metals, attaining extraction yields of over 90% in some cases.

Key words: Biomining • Microbial decomposition • Pyrite • Lixiviant • *Thiobacillus thiooxidans* • *Thiobacillus caldus* • *Leptospirillum ferrooxidans*

INTRODUCTION

Our ability to harness the natural capability of certain microbes to decompose a variety of mineral deposits is an old process that dates back to Roman times in the first century BC and probably the Phoenicians before that [1-2]. Those early miners used microbial activity to leach copper from ore without being aware that microbes were involved but now with increasing research trend in mineral biotechnology our interest toward the phenomena has grown up and has given some potential results which bring the revolution in mining industry.

As the world wide high grade ore reserves are falling day at appalling rate as most are worked out because of high metal demand, traditional techniques like pyrometallurgy and chemical processings are becoming more and more economically inviable. Micro organisms bear a clear advantage over it, as not only they offer an economically viable option but is also clean technology. Microbes such as bacteria and fungi convert metal compounds into their water-soluble forms and are biocatalysts of these leaching processes [3]. Additionally, applying microbiological solubilisation processes, it is possible to recover metal values from industrial wastes which can serve as secondary raw materials. Now with the gaining importance this mechanism is being used to recover metals such as gold, copper, iron, uranium.

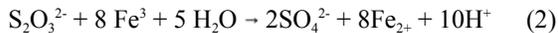
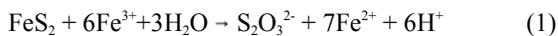
THE PROCESS

Biological Tools: A variety of mineral oxidizing bacteria readily found can easily oxidize iron and sulfur containing minerals. These include the iron- and sulfur-oxidizing *Acidithiobacillus ferrooxidans* (previously, *Thiobacillus ferrooxidans*), the sulfur-oxidizing *Acidithiobacillus thiooxidans* (previously *Thiobacillus thiooxidans*) and *Acidithiobacillus caldus* (previously, *Thiobacillus caldus*) and the iron-oxidizing *Leptospirillum ferrooxidans* and *Leptospirillum ferriphilum*[4-6].

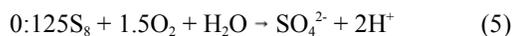
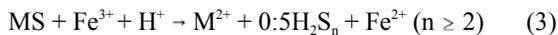
Several species of fungi can be used for biomining. Experiments have shown, that two fungal strains *Aspergillus niger* and *Penicillium simplicissimum* were able to mobilize Cu and Sn by 65% and Al, Ni, Pb and Zn by more than 95% [7]. Similarly, 'Phytomining' is based on the tendency of some plant species to bioaccumulate excessive amounts of metals from their host rock. The plants, called *hyperaccumulators* are grown on highly mineralized soils or post-mine lands and their yield (bio-ore) is used as a pure metal source [8-9]. Compared to the bacterial mining, these technologies are not so popular primarily because of the longevity of these processes and so their unprofitability.

Mining Mechanism: Microorganisms involved in biomining actually gain energy by breaking down minerals into their constituent elements. The mineral dissolution reaction is not identical for all metal sulfides. Sand and coworkers [10] have observed that the oxidation of different metal sulfides proceeds via different intermediates. They proposed a *thiosulfate mechanism* for the oxidation of acid-insoluble metal sulfides such as pyrite (FeS₂) and molybdenite (MoS₂) and a *polysulfide mechanism* for acid-soluble metal sulfides such as sphalerite (ZnS), chalcopyrite (CuFeS₂), or galena (PbS).

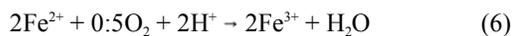
In the *thiosulfate mechanism*, solubilization is through ferric iron attack on the acid-insoluble metal sulfides, with thiosulfate being the main intermediate and sulfates the main end-product. Using pyrite as an example, the reactions proposed by Schippers and Sand [10] are:



In the case of the *polysulfide mechanism*, solubilization of the acid-soluble metal sulfide is through a combined attack by ferric iron and protons, with elemental sulfur as the main intermediate. This elemental sulfur is relatively stable, but can be oxidized to sulfate by sulfur-oxidizing microbes (Eqns 3-5).



This explains why strictly sulfur-oxidizing bacteria, such as *A. thiooxidans* or *A. caldus*, are able to leach some metal sulfides but not others. The ferrous iron produced during metal dissolution and biomining might also be reoxidized by iron-oxidizing organisms to ferric iron.



The role of the microorganisms in the solubilization of metal sulfides is, therefore, to provide sulfuric acid (Eqn (5)) for a proton attack and to keep the iron in the oxidized ferric state (Eqn (6)) for an oxidative attack on the mineral.

Effects of Temperature and pH: Physical conditions like temperature and pH are although the inherent property of micro-organism and so vary with micro organisms; still it is mainly decided by the dominant bacteria in the consortium like *T. ferrooxidans* and *Leptospirillum ferrooxidans*. The major reason for the dominance of '*Leptospirillum*' and *T. ferrooxidans* in industrial processes is almost certainly the Fe³⁺/Fe²⁺ ratio i.e. redox potential [11]. However, there may be other reasons which contribute to the dominance. The optimum pH for the growth of *T. ferrooxidans* is within the range pH 1.8-2.5, whereas *L. ferrooxidans* is more acid resistant than *T. ferrooxidans* and will grow at a pH of 1-2 [12]. With regard to temperature, *T. ferrooxidans* is more tolerant of low temperatures and less tolerant of high temperatures than is *L. ferrooxidans*. Some strains of *T. ferrooxidans* are able to oxidize pyrite at temperatures as low as 10°C (Norris, 1990) but 30-35°C is considered to be optimal. *Leptospirillum*-like bacteria have been reported to have an upper limit of around 45°C [13] with a lower limit of about 20°C [14]. The majority of continuous-flow biooxidation processes which are used to treat gold-bearing arsenopyrite ores or concentrates operate at 40 °C and pH 1-6 [15].

Mining Techniques: The two major processes used in biomining are percolation and agitation techniques. Percolation technique involves the percolation of a lixiviant through a static bed, whereas agitation technique involves finer particle sizes agitated in a lixiviant. Due to the large-scale operations involved in bacterial mining, percolation technique is preferred commercially [16].

The principal commercial methods are *in situ*, dump, heap and vat leaching. *In situ* leaching involves pumping of solution and air under pressure into a mine or into ore bodies made permeable by explosive charging. The resulting metal-enriched solutions are recovered through wells drilled below the ore body [17-18]. Three types of ore bodies are generally considered for *in situ* leaching: surface deposits above the water table, surface deposits below the water table and deep deposits below the water table.

Dump leaching involves uncrushed waste rock which is piled up. These dumps generally contain about 0.1-0.5% copper, too low to recover profitably by conventional procedures. Some of these dumps are huge, containing in excess of 10 million tons of waste rock.

Heap leaching requires the preparation of the ore, primarily size reduction, so as to maximize mineral-lixiviant interaction and the laying of an impermeable base to prevent lixiviant loss and pollution of water bodies.

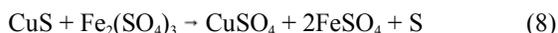
Essentially, both dump and heap leaching involve the application of the lixiviant to the top of the dump or heap surface and the recovery of metal laden solution that seeps to the bottom by gravity flow [19]. The dilute sulphuric acid sprinkled on top percolates down through the dump, lowering the pH and promoting the growth of acidophilic microorganisms. The acid run-off is collected at the bottom of the dump, from where it is pumped to a recovery station. Metal is extracted from the acid run-off by cementation or solvent extraction or electrowinning.

Vat leaching as currently applied to oxide ores involves the dissolution of crushed materials in a confined tank. More controls can be brought in for enhanced recovery by the use of bioreactors, though necessarily these involve higher costs. However for ore concentrates and precious metals they are being considered actively.

METALS RECOVERED IN BIOMINING PROCESSES

For many years biomining was thought to be a technology for the recovery of metals from low-grade ores, but today is being used as main process for recovery of copper and as important pretreatment step for gold recovery in their respective mining processes.

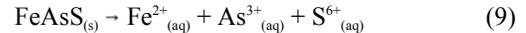
Biomining of Copper: Biomining of copper demands conversion of water-insoluble copper sulfides to water-soluble copper sulfates. Copper ores such as chalcocite (Cu₂S) or covellite (CuS) are crushed, acidified with sulfuric acid and agglomerated in rotating drums to bind fine material to courser particles before piling in heaps [16]. The heaps are then irrigated with an iron-containing solution which percolates through the heap and bacteria growing on the surface of the ore and in solution catalyze the release of copper. The ferric iron generated by the bacteria plays an important role in the production of copper sulfate.



The charged leach solution containing 0.5 to 2.0 g/l soluble copper and up to 20 g/l iron is collected and sent to a recovery plant [20]. The most common methods for copper recovery are by precipitation using large cementation unit, electrowinning or solvent extraction followed by electrowinning. The latter procedure produces the highest grade of copper [16].

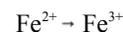
Bio-Discharge of Gold: Gold is usually recovered from ores by solubilisation with a cyanide solution and recovery of metal from the solution. In ores known as refractory, small particles of gold are covered by insoluble sulfides. While biooxidation process, bacteria partially oxidize the sulfide coating covering the gold microparticles in ores and concentrates [15].

In first stage, bacteria catalyse the breakdown of the mineral arsenopyrite (FeAsS) by oxidising the sulfur and metal (in this case arsenic ions) to higher oxidation states whilst reducing dioxygen by H₂ and Fe³⁺. This allows the soluble products to dissolve.

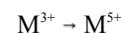


This process actually occurs at the cell membrane of the bacteria. The electrons pass into the cells and are used in biochemical processes to produce energy for the bacteria to reduce oxygen molecules to water.

In second stage, bacteria then oxidise Fe²⁺ to Fe³⁺ (whilst reducing O₂).

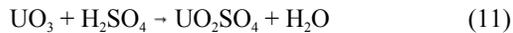


They then oxidise the metal to a higher positive oxidation state. With the electrons gained from that, they reduce Fe³⁺ to Fe²⁺ to continue the cycle.



The gold is now separated from the ore and in solution. Gold recovery from refractory minerals can increase from 15-30% to 85-95% after biooxidation [21]. A major drawback of the biooxidation compared with the physicochemical pretreatment processes is that in many cases the consumption of cyanide in the subsequent gold-recovery process is considerably higher following biooxidation.

Uranium Recovery: Uranium recovery proceeds in very similar way to copper recovery. Much like copper, uranium is recovered by the conversion of insoluble uranium oxides to soluble sulfates through the action of ferric iron and sulfuric acid produced by microbes.



Bacterial activity is limited to oxidation of pyrite and ferrous ion [22]. Biomining has been successfully used to obtain uranium from waste gold ore.

Biomining of Other Metals: Metals which are present in an insoluble reduced sulfur form and which are turned in soluble when oxidized to a sulfate may be potentially recovered by biomining. This includes minerals containing NiS and ZnS, cobalt-containing pyrite etc. Lead is recovered from the pregnant lead acetate containing solution and the solution may subsequently be recycled to further leaching of lead sulfidic minerals or lead sulfide containing particles [23]. Although biomining provides the possibility of recovering metals from many low-grade deposits that would otherwise be considered waste, its application greatly depends on the value of the metal to be recovered [24-25]. A major challenge is to find a suitable match between an ore body and biomining technology and to identify suitable concentration and size which allow economic recovery.

FUTURE PROSPECTS

The future of biomining is challenging, as it offers advantages of operational simplicity, low capital and operating cost and shorter construction times that no other alternative process can provide. In addition, minimum environmental impact and the use of this technology in the mining industry is set to increase.

Once commercial scale high-temperature processes have been designed, the variety of minerals that will become amenable to biomining will increase. Although the viability of microbes that flourish at temperatures 55°C is not yet well-proven commercially, it appears that one can isolate iron- or/and sulfur-oxidizing organisms for whatever temperature is required, up to at least 80°C. Therefore, where suitable microbes for mineral biodegradation at a given temperature are not yet known, they can probably be found.

Increased concern regarding the effect of mining on the environment is likely to improve the competitive advantage of microbially based metal recovery processes. The enforcement of more stringent legislation to limit environmental pollution would make biomining more attractive.

REFERENCES

1. Brierley, C.L., 1982. Microbiological mining. *Sci. Am.* 247: 42-51.
2. Rawlings, D.E., 2002. Heavy metal mining using microbes. *Annu. Rev. Microbiol.*, 56: 65-91.
3. Acharya, R., 1990. Bacterial leaching: a potential for developing countries, *Genetic Engineering and Biotechnology Monitor*, 27: 57-58.
4. Clark, D.A. and P.R. Norris, 1996. *Acidimicrobium ferrooxidans* gen. nov., sp. nov.: mixed-culture ferrous iron oxidation with *Sulfobacillus* species. *Microbiology*, 142: 785-790.
5. Nagpal, S. *et al.* 1993. Effect of carbon dioxide concentration on the bioleaching of a pyrite-arsenopyrite ore concentrates. *Biotechnol. Bioeng.* 41: 459-464.
6. Leduc, L.G. and G.D. Ferroni, 1994. The chemolithotrophic bacterium *Thiobacillus ferrooxidans*. *FEMS Microbiol. Rev.*, 14: 103-120.
7. Brauer, H., 1991. Growth of Fungi and Bacteria in the Reciprocating Jet Bioreactor, *Bioprocess Engineering*, 6: 1-15.
8. Anderson, C.W.N., R.R. Brooks, Chiaruccia, C.J. Lacoste, M. Leblanc, B.H. Robinson, R. Simcock and R.B. Steward, 1999. Phytomining for thallium, nickel and gold. *J. Geochem. Explor.*, 67: 407-415.
9. Nedelkoska, T.V. and P.M. Doran, 2000. Characteristics of heavy metal uptake by plant species with potential for phytoremediation and phytomining. *Minerals Engineering*, 13(5): 549-561.
10. Schippers, A. and W. Sand, 1999. Bacterial leaching of metal sulfides proceeds by two indirect mechanisms via thiosulfate or via polysulfides and sulfur. *Appl. Environ. Microbiol.*, 65: 319-321.
11. May, N., D.E. Ralph and G.S. Hansford, 1997. Dynamic redox potential measurement for determining the ferric leach kinetics of pyrite. *Miner Eng.*, 10: 1279-1290.
12. Norris, P.R., 1983. Iron and mineral oxidation with *Leptospirillum*-like bacteria. In *Recent Progress in Biohydrometallurgy*, pp: 83-96. Edited by G. Rossi and A.E. Torma. Iglesias, Italy, Associazione Mineraria Sarda.

13. Norris, P.R., L. Parrot and R.M. Marsh, 1986. Moderately thermophilic mineral-oxidizing bacteria. *Biotechnol. Bioeng. Symp.*, 16: 253-262.
14. Sand, W., T. Gerke, R. Hallmann, K. Rhode, B. Sobokte and S. Wentzien, 1993. In situ bioleaching of metal sulfides: the importance of *Leptospirillum ferrooxidans*. In *Biohydrometallurgical Technologies*, I: 15-27.
15. Dew, D.W., E.N. Lawson and J.L. Broadhurst, 1997. The Biox® process for biooxidation of gold-bearing ores or concentrates. In *Biomining: Theory, Microbes and Industrial Processes*, pp: 45-80.
16. Schnell, H.A., 1997. Bioleaching of copper. In *Biomining: Theory, Microbes and Industrial Processes*, pp: 21-43.
17. Brierley, C.L. and J.A. Brierley, 2000. Bioheap processes: operational requirements and techniques. *Proc. Randol Copper Hydromet Roundtable 2000*, Tucson, Ariz., Sept. 2000, pp: 95-103.
18. Bampton, K.F., F. Bologiannis, J.H. Canterford and A.N. Smith, 1983. Development of experimental in-situ leaching at the Mutooroo copper mine, South Australia. *Aus IMM Annual Conference*, Broken Hill, NSW July 1983, pp: 371-379.
19. Rawlings, D.E., 1997 (Ed). *Biomining: Theory, Microbes and Industrial Processes*, Springer-Verlag, Berlin.
20. Ismay, A., L. Rosato and D. McKinnon, 1986. Engineering prefeasibility for in-place bacterial leaching of copper, *Fundamental and Applied Biohydrometallurgy*, pp: 191-198.
21. Dew, D.H., 1995. Comparison of performance for continuous bio-oxidation of refractory gold ore flotation concentrates. In: Vargas, T., Jerez, C.A., Wiertz, J.V. and Toledo, H., eds. *Biohydrometallurgical Processing*, Vol.1. Universidad de Chile, Santiago, Chile. pp: 239-251.
22. McCready, R.G.L. and W.D. Gould, 1990. In *Microbial Mineral Recovery*, Erlich, H.L. and Brierley, C.L. (Eds.), pp: 107-126. McGraw-Hill, New York.
23. Geisler, R.A. and I.E. Pudington, 1996.. Treatment of lead sulfide bearing minerals. US Patent 5: 523-066.
24. Rawlings, D.E., 2002. *Annu. Rev. Microbiol.*, 56: 65-91.
25. Dew, D.W. and D.M. Miller, 1997. In *IBS Biomine '97*, pp: M7.1.1-9. Australian Mineral Foundation, Glenside, Australia.